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GEOPHYSICAL VARIABLES AND BEHAVIOR: LXIII. QUASI-EXPERIMENTAL EVIDENCE OF THE TECTONIC STRAIN THEORY OF LUMINOUS PHENOMENA: THE DERBY, COLORADO EARTHQUAKES [1]

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Summary.—This study provides the first quasi-experimental evidence for the Tectonic Strain Theory for luminous phenomena. Approximately 1500 earthquakes occurred near Derby, Colorado during the years 1962 through 1967 as a result of injection of several millions of gallons of industrial waste fluid into the crystalline bedrock. Correlations between numbers of luminous phenomena within successive 100-km rings from the injection site and the release of seismic energy gave significant coefficients for distances as great as 400 km. Lag/lead analyses between the monthly volume of fluid injection and the monthly numbers of luminous phenomena at various distances indicated that some process was diffusing away from the injection site at a rate of 50 to 100 km/month to distances as far as 300 km. Partial correlation analyses supported the hypothesis that both the luminous phenomena and the Derby quakes were generated by the stresses evoked by the amount of fluid injection during that period. Unprecedented increases in luminous phenomena occurred before releases of strain energy that exceeded magnitudes of 10^{17} ergs/month.

The tectonic strain theory, first proposed by Persinger (1976), states that both anomalous luminous phenomena and earthquakes are generated by tectonic stresses and strain. Although persistent, moderately strong correlations between numbers of reports of luminous phenomena and the release of seismic energy suggest a relationship (Persinger, 1983, 1984; Persinger & Derr, 1985a, 1985b, 1990; Derr & Persinger, 1986, 1989, 1990), they do not necessarily indicate causality. Experimental manipulation of stresses that precipitate moderately strong earthquakes is generally impossible because of ethical and economic considerations.

However, between the years 1962 and 1967 more than 1500 recorded earthquakes occurred during the injection of industrial waste fluid into deep strata in the Denver Basin. The quakes were considered a consequence of the release of elastic energy from stored tectonic strain within the crystalline bedrock. The energy release was precipitated by the fluid injection (millions of gallons per month) into the bedrock (Healy, Rubey, Griggs, & Raleigh,

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1968). Fluid pressure lowered the strength of the faults such that existing stresses could cause slip on those faults.

We reasoned that the Derby (Denver) quakes were an excellent quasi-experimental test of the tectonic strain theory. Three hypotheses were obvious: (1) if luminous phenomena were caused by the same processes that caused those earthquakes, then nearby luminous phenomena should have been correlated over time with the amount of fluid injection, (2) if luminous phenomena were coupled to strain accumulation processes, then unprecedented increases in the numbers of luminous phenomena should occur within the region when the release of seismic energy per month exceeded some threshold. Also, (3) the luminous phenomena nearest the site of stress accumulation (the Rocky Mountain Arsenal Well) should be most correlated with the amount of energy release.

To test these hypotheses, total numbers of earthquakes per month, fluid injected per month, and the amount of seismic energy released per month were estimated from published sources (Major & Simon, 1968). The calculation of the release of seismic energy was unusually accurate given the proximity of instrumentation and the systematic determination of earthquake magnitudes during this period.

Luminous phenomena were obtained from the UFOCAT computer file ("UFO catalog") from the Center for UFO Studies (CUFOS) as described by Saunders (1978). Unclassified and Types II through VI are the traditional classifications of earthquake-related luminous phenomena (Terada, 1931). The following are general descriptors of the UFOCAT "types" of luminous phenomena: II, continuous trajectory; III, noncontinuous trajectory with a single discontinuity of movement; IV, noncontinuous trajectory with multiple discontinuities of movement; V, proximity to the observer such that specific, unusual details were observed (e.g., differential distribution of colors within a luminous phenomenon); and VI, movement of the luminous phenomenon along or over the ground, close to the observer.

Redundant cases, defined as those with the same hour, day, month, year, and latitude-longitude details, were eliminated. Number of days in which luminous phenomena occurred per month for the years 1962 through 1967 were determined for each radial increment of 100 km from Derby (e.g., 0—100 km, 101—200 km, etc.) to a total radius of 600 km. Days with luminous phenomena per month were determined rather than total numbers of these phenomena to reduce the possible effects of single intense episodes; the correlation between total numbers of reports and numbers of days was 0.93. Both analyses of variance and Kruskal-Wallis tests (given the heterogeneity of variance) yielded no statistically significant ($p > .05$) differences in the numbers of days with luminous phenomena within any of these radial increments as a function of either months or seasons.

Fig. 1A shows the temporal relationship between the monthly totals of fluid injection, numbers of earthquakes, the energy release and the numbers of days with luminous phenomena within 100 km from Derby during the

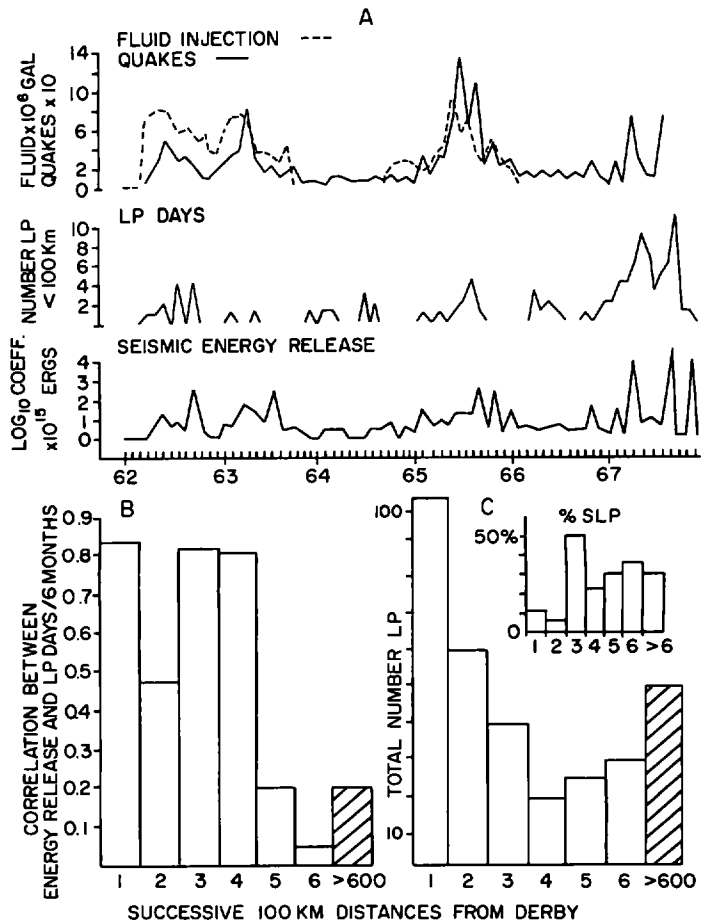

FIG. 1. (A) Total volume of fluid injection, numbers of earthquakes, numbers of luminous phenomena within 100 km of Derby, and energy release per month around Denver during the years 1962 through 1967. (B) Correlation between energy release per 6-mo. interval near Derby and the numbers of days with luminous phenomena per 6-mo. interval at various successive distances from Derby. (C) Total numbers of luminous phenomena as a function of 100-km increments from Derby. Specific luminous phenomena refer to reports that indicated distinctly unusual movements and visual properties.

period of and following the fluid injection. Visual inspection indicates that most of the days with luminous phenomena occurred during the months of most of the earthquakes that were presumably caused by, but occurred after,

the intervals of fluid injection. Unprecedented numbers of luminous phenomena occurred during 1967 when the energy release exceeded 100 ($\log_{10} = 2$ in the figure) $\times 10^{15}$ ergs, i.e., 10^{17} ergs per month. There were only four other months before 1967 when seismic energy release exceeded this value; three of them were associated with the only two major displays of luminous phenomena.

Fig. 1B shows the correlation between the amount of energy release per six-month increment for the years 1962 through 1967 and the numbers of days with luminous phenomena within successive 100-km distances from Derby. Statistically significant correlations existed between the numbers of days with luminous phenomena per month and energy release per month as far as 301 km to 400 km from Derby. The numbers of luminous phenomena per 100-km increment from Derby are shown in Fig. 1C. Most of the luminous phenomena occurred within 100 km of the injection site and then decreased exponentially with distance. However, this pattern must be evaluated cautiously because the potentially confounding factor of population density, which would affect the observation of luminous phenomena, was not accommodated. The insert in Fig. 1C represents the percentage of reports from the UFOCAT that were classified specifically as Type III through VI, specific luminous phenomena or SLP, defined by Derr and Persinger (1990); it indicates that closer luminous phenomena were designated as unclassified within the UFOCAT data base. This observation may not necessarily alter the interpretation of the results because the strongest correlations between the numbers of unclassified and specific classified cases occur with specific luminous phenomena (Derr & Persinger, 1990).

Previous analyses indicated that the correlations between monthly volumes of fluid injection and earthquakes were statistically significant (Healy, *et al.*, 1968). To ascertain whether significant intercorrelations between days with luminous phenomena, quakes, and fluid injection existed, the 29 months during which fluid was injected under pressure were analyzed; this period was actually composed of two separate intervals, March 1962 through September 1963 and April 1965 through February 1966. These intervals were selected because they were the periods of greatest man-made ("experimentally") induced strain.

To be consistent with the hypothesis, luminous phenomena within 100 km of the injection site should have been most correlated with the amount of fluid injection during the same months as the observations of luminous phenomena. As shown in Fig. 2A, this hypothesis was confirmed ($rho = 0.54$, $p < .001$). For control, we have always employed routine lag/lead procedures (Derr & Persinger, 1989). In this analysis, luminous phenomena within 100 km were not significantly correlated with the fluid injected during any of the six months before or after the luminous phenomena.

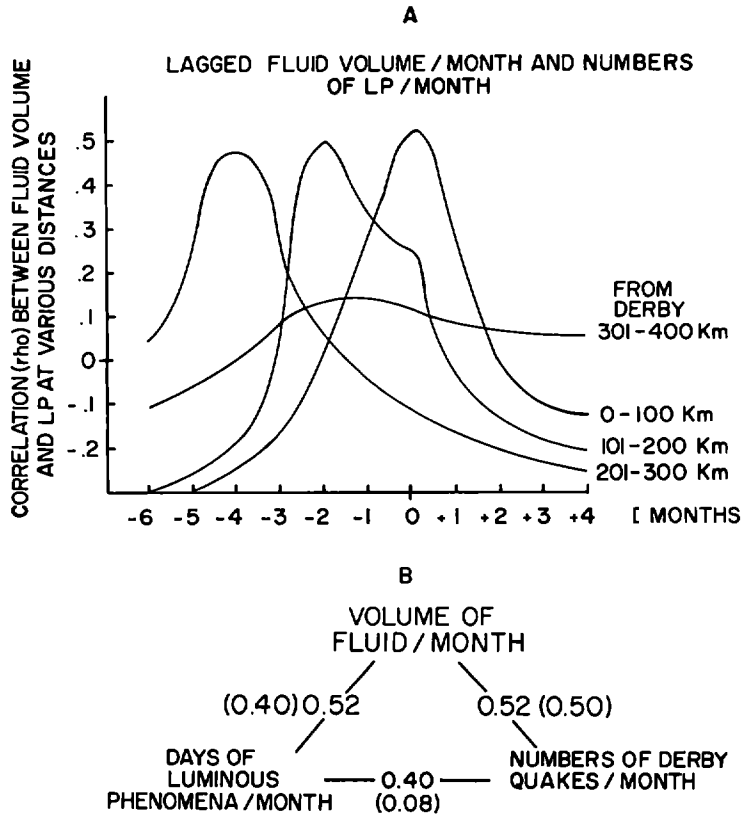

FIG. 2. (A) Smoothed curves connecting correlation coefficients for the relationship between the numbers of days with luminous phenomena per month within successive 100-km increments from Derby and the volume of fluid injection per month beneath Derby for each of the previous and consequent 6 mo. (B) Zero-order intercorrelations between measures of fluid injection days with luminous phenomena and quakes during 29 mo. of overpressure injection. Values in parenthesis indicate partial correlations after variance from the third variable has been removed.

Also consistent with the hypothesis, the numbers of days with luminous phenomena per month within 101 to 200 km from Derby were most highly correlated with the amount of fluid injected per month *two months before*, and the numbers of days with luminous phenomena within 201 to 300 km from Derby were significantly correlated only with the amount of fluid injected *four months before* the months during which there was an increase in days with luminous phenomena. Within the limits of the ± 6 month lag/lead computations, there were no statistically significant correlations between luminous phenomena and fluid injection beyond 300 km. To ensure the luminous phenomena within the different 100-km rings were related, lag/

lead correlational analyses were also completed. Luminous phenomena within 201—300-km distance were significantly correlated (*rho* = 0.60) with the luminous phenomena within the 101- to 200-km region two months before, and days with luminous phenomena in the 101- to 200-km region were most correlated (*rho* = 0.65) with luminous phenomena within 100 km of Derby two months before that.

To determine the shared sources of variance between the three-way intercorrelations between quantitative measures of quakes, fluid, and days with luminous phenomena per month within 100 km of Derby, square root transformations were completed on each measure to accommodate the assumptions of parametric analyses. The results are shown in Fig. 2B. The zero-order correlation coefficients were: (1) 0.52 ($p < .01$; 95% confidence interval of 0.17 to 0.70) between fluid volume per month and days with luminous phenomena per month, (2) 0.52 between numbers of quakes and fluid injection during this period, and (3) 0.40 between days with luminous phenomena and numbers of Derby quakes (all degrees of freedom = 29).

When the shared variance between numbers of earthquakes and fluid volume was removed, the correlation between days with luminous phenomena and fluid volume remained statistically significant ($r = 0.40$, $p < .05$); when the shared variance between days with luminous phenomena and fluid volume was removed, the correlation between fluid volume and numbers of quakes remained significant ($r = 0.50$). However, when the shared variance between fluid volume and days with luminous phenomena was removed, the correlation between those days and number of earthquakes was no longer statistically significant (0.08). According to the assumptions of partial correlational analyses, the results suggest that the injection of millions of gallons of fluid controlled the occurrence of *both* the luminous phenomena and the earthquakes.

The results of these analyses are significant both for the support of the tectonic strain theory and for previous assumptions concerning the limits of strain-field propagation. Although these tectonic stress-related earthquakes moved along a plane towards the South Platte River, they were relatively local. However, numbers of luminous phenomena as far as 300 km from the site were correlated with the amount of seismic energy release. These distances are similar to those noted between very energetic seismicity and the luminous phenomena for other areas (Derr & Persinger, 1986, 1989; Persinger & Derr, 1985a, 1985b).

This study is the first quasi-experimental evidence for the tectonic strain theory; all three of our initial hypotheses were confirmed. We had not expected that a suggestion for mechanism might be indicated. In the present analyses, however, the systematic temporal lag between overpressure fluid injection and the increase in luminous phenomena at successive distances

from Derby, indicates that some process was slowly migrating away or diffusing from the Arsenal well. Simple estimates indicate that the process was moving at between 50 and 100 km per month up to distances of approximately 300 km. These speeds are within the range of those noted for the migration of luminous phenomena towards an imminent epicenter (Persinger & Derr, 1990).

The second author (Persinger, 1976, 1984, 1988; Persinger & Derr, 1985a, 1985b) has suggested that the luminous phenomena are associated with a strain field that moves through the crust; the physical equivalent of this hypothetical construct is assumed to be caused by tectonic stresses and to create the luminous phenomena by transformation of elastic energy within focal susceptible regions, such as faults or uplifts. The present results also raise the question of whether water might be able to move through the crust fast enough to account for the observed luminous phenomena, or whether fluid injection, in this case associated with industrial chemical wastes, could otherwise affect the water pressure at significant distances from the injection site. According to the dilatancy model (Rikitake, 1976), water diffusion into newly created pores within the rock may contribute to the precipitation of earthquakes and their nontectonic precursors.

It is highly unlikely that the waste fluid itself was traveling that far that fast, but evidently some process was diffusing away from the injection site at a rate of 50 to 100 km/month. That process was most likely tectonic strain, propagating aseismically, and driven by small earthquakes which were caused by the pressure of the fluid injected at the base of the well. Seismic waves would have radiated at the velocities appropriate for compressional and shear waves of the medium, but the strain would have radiated more slowly, e.g., 50 to 100 km/month.

This pressure wave, under the right conditions, might have expelled fluids from rock formations by fracturing their pressure seals (Cathles, 1990). An hydraulic system, with fluids driving faulting at the injection well and faulting driving fluids where the luminous phenomena were observed (Sibson, 1981), would have been created. In between, the hydraulic pressure would have been conveyed by propagating tectonic strain. Exoelectron emission (cf. Brady & Rowell, 1986) from the faulting could have created the charge which was carried by the conducting fluid in the formation and by steel well casings where they existed. When these pathways reached the surface, the potential for creation of a luminous phenomenon would have occurred.

Having established the statistical connection between fluid injection and luminous phenomena, we can refer to the well-established relation between fluid pressure and tectonics (Hubbert & Rubey, 1959) to say that the Derby fluid injection provided quasi-experimental evidence for the tectonic strain

theory and suggests an electro-hydraulic mechanism for the initial conveyance of the elastic energy in the earth, creation of the electrical potential, and transport of the charge to the surface. The mechanism for the creation of the luminosity itself remains unknown, although it is most likely to be similar to that of the creation of ball lightning, which many of these luminosities closely resemble.

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